Method for analysing the positioning of components in mechanical assemblies

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Abstract. This article deals with the analysis of the part positioning in models of mechanical assemblies and its systematic recording. This analysis is essential in the process of obtaining the functional dimensioning of each component that meets the geometric requirements set by the specifications.
The method is derived from knowledge of the nominal models of each component and the whole assembly. The first phase of functional dimensioning is based on the analysis of the positioning of each part in any possible operating state. The part positioning depends on the identification and definition of the contact surfaces and their order of preponderance. This method makes it possible to obtain the dimensioning of the contact surfaces by means of position specifications. In addition, by precisely defining the part positioning, the ISO dimensioning can be carried out in such a way that the consistency of the dimensioning with the requirements can be easily verified.
Every functional requirement will generate a tolerance stackup of influencing dimensions that must be recorded. Considering that an assembly or device may have several operating states, parts may have several operating positions which shall be analyzed and provide different dimension tolerance stackups and functional dimensions.
For the above reasons, the method must use the language common to all these environments, which is none other than the ISO-GPS language.

Keywords: ISO-GPS Language, Location Tolerances, Functional Requirements, Tolerance Analysis.

1 Introduction

Functional dimensioning is a way of defining the geometry that ensures fulfilment of the functional requirements determined by functional product analysis methods. This dimensioning gives preference to the definition of the geometrical characteristics of each of the parts on which the correct functioning of a device depends. ISO dimensioning makes possible to translate all these requirements into ISO specifications that can be used by conceptors, manufacturers and metrologists. ISO dimensioning is an integral part of the functional dimensioning process because it is the language in which these requirements are expressed. It was developed for highly technical profes-sional

environments and is not easily applicable to mid-level professional and aca-demic environments.
ISO dimensions correspond to specifications of three different types (dimensional, by tolerance zone and by pattern) and will always be presented on nominal models (2D or 3D) of individual parts. Accurately understanding ISO specifications does not imply knowing and understanding their specific functional purpose. Understanding the content of a message does not imply knowing the context and purpose for which it is written. When the language is complex and the reason is not understood, there is a certain rejection of the message.
Specifications or ISO dimensions provide the surface tolerances of the various in-fluencing parts, but will also provide the references and functional requirements of a geometric nature of an assembly and of each component.
Each operating state depends on the position of the different parts, which is called part positioning. The analysis of the part positioning is based on the study of the con-tacts between each pair of parts that are physically in contact. This study is based on a procedure traditionally known as chain or dimensional stacking up. If the contacts are parallel plane supports, the link dimensions of this chain could be traditional (non-ISO) dimensions with dimensional tolerances. If the positioning only requires simple parallel contacts, but they are integrated by several interfaces, we need to use ISO specifications or dimensions and create two- or three-dimensional stack-ups.
ISO dimensions or specifications will not only provide tolerances of the surfaces of the different influential parts, but will also provide the referential and functional re-quirements of a geometrical nature of the devices. ISO dimensioning is an integral part of the functional dimensioning process because it is the language of expression of these requirements.
We suggest a logical, systematic and rigorous procedure to define precisely how each part is in contact with other parts in each state of functioning. This procedure is proposed for pedagogical purposes in order to allow a precise understanding of the placement and the determination of the reference systems that will allow us to obtain the ISO specifications and to understand why specific ISO specifications are required for each part and not others.
Our motivation is the transfer of knowledge in an academic environment and by students' demands on teaching. In the following sections, we will pay particular atten-tion to a method of positioning parts that includes: a functional analysis, technical functional analysis tables, block diagrams and lists of interfaces, also the description of part positioning and the representation report, and functional requirements dimen-sioning and stackups.

2 Method of part positioning

The fulfilment of the various functional requirements of a given device depends on observance of certain geometrical dimensions and characteristics. The appropriate measures are the functional dimensions at their nominal value. The modelling of each imperfect physical part makes it necessary to determine the admissible devia-tions from these nominal values (tolerances), which are expressed in ISO geometrical

specifications [1, 2]. The main output product of the conceptual design phase is the set of definition drawings for each of the components.
This whole process (functional dimensioning) begins in the preliminary project phase with the determination of the technological solution adopted and is not con-cluded until just before the industrialization of the product. It is usually a long and complex process in which many professionals are involved, so it is advisable to adopt a working method that allows for accuracy and complete recording of the infor-mation and communica-tion between all the participants. In addition, it must allow for the ISO specifications to be completed and amended.
As we want to propose a method that is as easy to understand as possible, we pre-sent it at the beginning of the project, considering that we are in the design phase of the project. There is an overall drawing or 3D model [3] corresponding to the techno-logi-cal solution adopted, the customer needs requirements and the geometric tech-nical functional analysis [4]. These are the fundamental elements because they de-termine the nominal model that we must specify and the set of geometric require-ments that the product must meet as agreed with the client. We start from the as-sumption that the mechanism is known, and the parts are rigid; to this end we have the CAD model (2D or 3D) which defines the theoretical, perfect shapes and dimen-sions; it is the represen-tation of an idea (see Fig. 1).

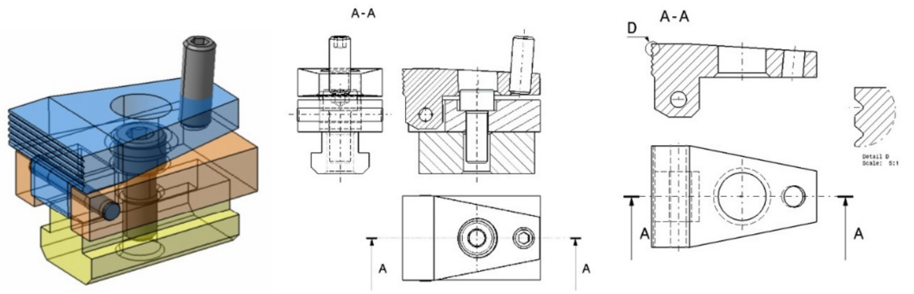

Fig. 1. Representation of the technological solution adopted

The method aims to determine the ISO dimensions of parts of a relatively complex assembly in an agile way. It therefore proposes the use of graphical tools and data tables that can be integrated, used and capitalized in the various project dossiers [5].

2.1 Analysis of the functional structure of a mechanism

According to the technical functional analysis procedures, kinematic diagrams, rela-tionship graphs, joint graphs or functional flow diagrams must be generated from the CAD model to represent the functional structure of the product in sub-assemblies (see Fig. 2). The kinematic diagrams also help to identify the equivalence groups and the degrees of freedom or relative motions possible between the different sub-assemblies or blocks (set of interlocking parts) that make up the product. The relationship diagrams model the structure of the mechanism and allow it to be broken down into a fixed block and various moving blocks [6].

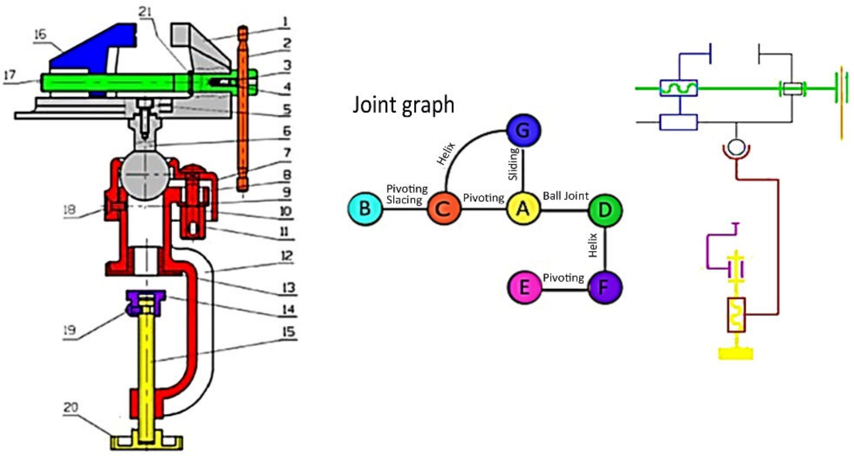

Fig. 2. Kinematic diagrams and relationship graphs

Functional flow diagrams allow us to identify the joints or interfaces between each component or sub-assembly and the constraints of the 3D CAD model assembly. The base part of a block is the most important part because it can support several parts and it is advisable to maintain this base part character throughout the process because it conditions the composition of the dimensional tolerance stackups or loops and the dimensioning will be slightly different if we change the base.

2.2 Technical functional analysis tables

The technical functional analysis to be carried out is capitalized in a Technical Functional Analysis Table (TFAT). This table makes it possible to identify and bring together the functional requirements that must correspond to a specific ISO dimension of the definition plane of each part and the extreme values that it can adopt, includ-ing a safety limit that ensures a control of the risk of functional failure. We will adopt the method of drawing up data tables because they are a presentation already used by the TFATs and allow the use of well-known spreadsheet-type software tools [4, 7].
The TFAT tables shall identify the desired and undesired joints between parts and part surfaces involved in the functional requirement. For each part, the elementary technical functions (ETF) shall be recorded for each joint characterized by the geo-metrical functional conditions (GFC). The TFAT may contain for each part, in a number of columns, the basic engineering functions, the stresses, the acceptance criteria of the basic engineering functions, the failure mode analysis, the effects and their criticality FMAEC, the hierarchy of characteristics and the ISO and surface finish specifications (GPS specifications) [8]. The more complete the TFAT, the easier it is to check the consistency

of the designed model with the functional requirements of the assembly although in a first approximation the columns of the GPS specifica-tions will be enough.

2.3 Block diagram. Creating the list of interfaces

The list of surfaces for each joint is obtained from the block diagram. The block diagram makes it possible to identify all the relationships between components. The joint elementary technical functions (ETFs) are represented in the block diagrams by a thin line corresponding to at least one ETF [8]. Each joint (desired or undesired) corresponds to a geometrical functional condition or a length or angle value, i.e. a dimensional condition and end faces (see Fig. 3).

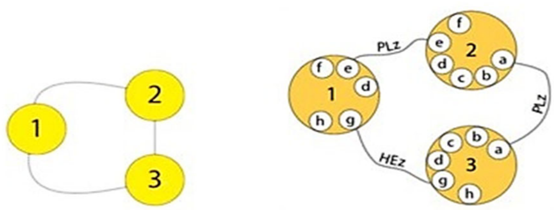

Fig. 3. Contact diagram (left) and elementary contact diagram (right)

The block diagram is a representation of joints, not oriented, i.e. does not allow to establish whether a part positions or is positioned by another part. As we have seen in the structuring of the mechanism, there is always a part that acts as a basis, so there is an orientation in the joints. This orientation of the joints can be determined by developing a provisional assembly range (see Fig. 4) to identify which part acts as the basis of the assembly or which is the support part on which another of each pair of parts is placed in position [9, 10]. The provisional assembly diagram will allow us to identify which part we should start analyzing the positioning of the parts involved in a condition, in which order to go through the tolerance stackup of functional dimensions and an approximation of the preponderance of each interface in the joint.

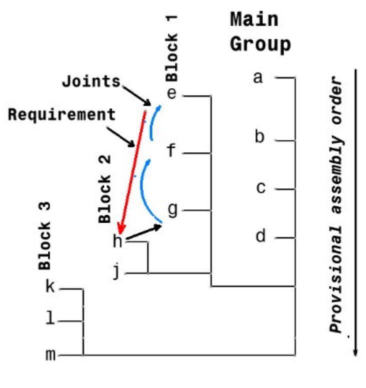

Fig. 4. Provisional assembly range

We can capitalize on this analysis by adding 'Elements in Contact' columns to the TFAT [4], describing each interface and an order of preponderance.

2.4 Designation of the parts of a mechanism

In the vast majority of cases, specifications are associated with surfaces that form the interfaces or joint that determine the part positioning. Therefore, the first step in functional dimensioning is to identify each of the surfaces that make up each part. Since we are starting from a CAD model, we have the drawings of each part (accord-ing to ISO 128) [11], but without the functional dimensions.
A surface code (one or two small Latin letters corresponding to the name of the part and a correlative number) must be noted to identify each surface of each part (see Fig. 5). This surface code should not include the item number just any other nu-merical value.

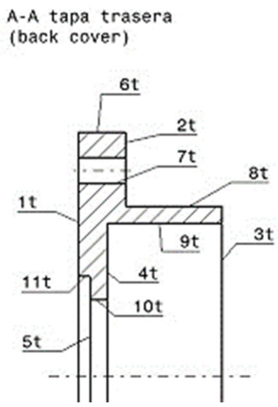

Fig. 5. Surfaces identification

This first step is very simple but important because it allows the identification of each surface of each component and the elaboration of the elementary contact graph that will model the elementary contacts between surfaces. The graph of elementary contact is an extension of the relationship graph that allows the identification of each intervening surface and the type of kinematic contact between them [6, 10].

2.5 Description of part positioning

States or stages of operation

The next step is to identify each phase or operating stage of the pre-project device. For each operating phase, it is necessary to obtain a structure diagram, an assembly analysis drawing and, above all, a table detailing the contacts or interfaces that characterize each functional phase and each of the surfaces involved. As the number of functional stages is usually not very large, a number and a designation are usually sufficient to identify each operational stage [10].

Functional conditions: condition dimensions

At each stage of operating, a number of geometrical functional conditions must be met simultaneously and independently, defining a set of functional tolerance stackups.

The tolerance stackups of dimensions allow the identification of the intervening parts. Once all the parts involved in the tolerance stackup have been identified and before looking for the functional dimensions of each part, it is necessary to analyze how each part is positioned in relation to the previous one, i.e. it is necessary to study each contact in the tolerance stackup.

Contacts can only be only of a few relatively simple types and depend on so-called positioning entities. Positioning entities can be of the simple or support type, or of the bilateral or fit type (see Fig. 6).

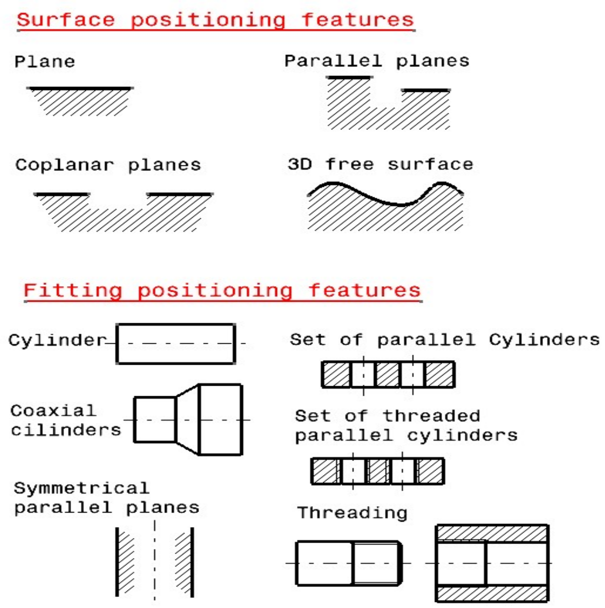

Fig. 6. Types of positioning entities

These positioning entities constitute the datum systems of the ISO specifications. This will allow us to establish the datum systems of the ISO dimensioning of each part, the preponderance of each datum and to define the existence of clearances, clamps or supports or intervening elements between each interface [10].

Representation of the part positioning by means of a report.

Regardless of the type of tolerance stackup and the difficulty of calculating ISO dimensions, tolerance stackups share the concept of part positioning, i.e. how one part is positioned in relation to another. Each part adopts a position in relation to the rest of the mechanism through a contact that can be described by a part positioning table. In order to better control and capitalize on the characteristics of the part positioning, it is proposed to adopt the Anselmetti's part positioning table [10] (see Fig. 7) because its layout is very clear and understandable. It also allows: to study each part separately, to validate a project very quickly before proceeding to dimensioning, and for the author to easily add dimensioning suggestions.

Part or block	Code	Config.	Author
Piston	p	2	Author

	Primary		Secondary		Tertiary	
Feature	Coaxial Cylinders		Plane			
Surface	**A**	2p,6p	**C**	10p		
Interface	Clearance		Contact			
Feature	Coaxial Cylinders		Plane			
Surface	**D**	1f,17e	**F**	20e		

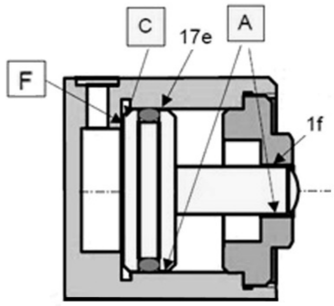

Fig. 7. Part positioning table

Each part-part joint consists of 1, 2 or 3 interfaces. Each interface eliminates several degrees of freedom, which makes it possible to arrange them according to an order of preponderance: primary, secondary and tertiary. Each interface, in turn, is made up of positioning entities depending on whether there is a support or any type of fit between the pair of parts being analyzed. The 1st, 2nd and 3rd positioning entities will form the datum system of the ISO dimension. In the support part, it is necessary to determine the corresponding positioning entities that will form the support system, also called auxiliary datum systems [8, 10].

All of this information must be presented on a part set-up report, which includes the set-up table and a schematic drawing of the contact. This drawing must show the two parts and any other parts that may be involved in the contact, such as seals, pins, bearings, etc. The table will have all the data clearly identified and we will be able to fill in all the boxes in an orderly manner and know if any data is missing. Before completing the part positioning table, it is advisable to make a schematic drawing of the part under study and the support part. On this drawing, the positioning surfaces shall be highlighted by the part designation and a number (aforementioned), colored according to their order of preponderance (red, green, blue) and named with a boxed capital Latin letter (A, B, C for the part reference system and D, E, F for the support part system).

ISO dimensioning is essentially based on the datum systems that model the contacts between parts and the location and orientation specifications. Supplementary information makes it possible to optimize the specification and to indicate only what is necessary, such as the cases of virtual state, projected areas and restricted areas.

Each state of operation will require a part positioning report or sheet for all the parts involved, starting with the last part assembled and ending with the base part. Each part of the assembly must therefore have as many part positioning reports as the number of states in which it is involved [10, 12].

The part positioning study makes it possible to establish the ISO specifications necessary for assembly, assemblability, contact quality assurance and the determination of the datum systems necessary for the functional dimensioning of each part or block.

2.6 Dimensioning to a functional requirement. Tolerance stackups

In an operational state, the mechanism must fulfil several geometric functional requirements, which are translated into geometric values (position, orientation, macro or micro geometric dimensions) that define the validation criteria. The expression of these functional requirements is the ISO specification.

For each condition dimension, we must determine the tolerance stackup and impose the necessary specifications on each link part (see Fig. 8). The requirements expressed by the tolerance stackups are also expressed by inequalities. The solution of the system of inequalities implies a distribution of tolerances that must be made by means of manufacturing criteria and independence between them. This distribution of tolerances is beyond the scope of this paper.

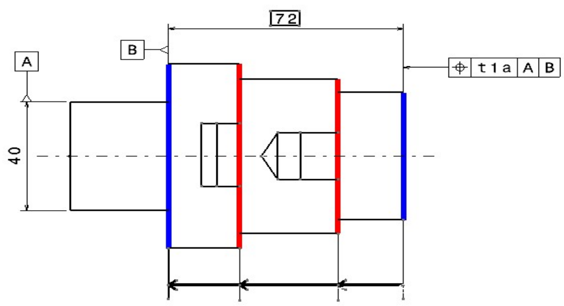

Fig. 8. Tolerance stackup

We will identify each tolerance width with a code (t + correlative number of the width + alias of the part, e.g. t3s: tolerance width 3 of part s, support). In this way we will know which tolerance widths to calculate and if any are missing.

The tolerance stackups can be of various types, giving rise to problems of varying degrees of difficulty depending on their nature, whether they are 1, 2 or 3 dimensional, whether they have supports inclined to the direction of the requirement and whether they form loops or not. From these tolerance stackups of dimensions, the functional dimensions of each of the intervening parts are obtained. The complexity of the process of obtaining each functional dimension depends on the type of tolerance stackup, ranging from simple to highly complex cases.

The simplest procedure implements the traditional method of dimensioning with an adaptation to ISO dimensioning and the use of references that we have defined. It is very effective in the case of unidirectional tolerance stackups, which are the most commonly used, and allows the ISO specification writing process to be understood without the need to master GPS standards and rules as is the case with 2D or 3D tolerance stackups [13, 14].

The functional requirements control the position of the terminal surface in a direction normal to the terminal surface. For flat end surfaces the positioning distance shall be measured in a direction normal to the planes and bounded by the contours. For cylindrical surfaces the direction in one or more (often 8) radial directions. For complex surfaces, the normal must be determined at the critical points for meeting the functional requirement under consideration. This is called the direction of analysis and is of paramount importance for 2D and 3D tolerance stackups.

In the case of one-dimensional tolerance stackups, each condition dimension shall require a position specification and a TED dimension; the datum system shall be the datum system of the base part for positioning in the environment outside the studied perimeter. For 1D strings the direction of analysis shall coincide with the direction of the condition dimension and of the item specification. For each intermediate link part, the contact surfaces supporting another part shall be referenced with respect to the positioning surfaces of that part.

For each tolerance stackups, it is necessary to prepare a sheet containing a table for the calculation of nominal dimensions and deviations, as well as schematic drawings of the set of parts involved and of each part (see Fig. 9). The first step is to identify the end faces on a schematic analysis drawing by highlighting the end faces, intermediate bearing surfaces and removing from the drawing all parts that are not required for the positioning of each link part.

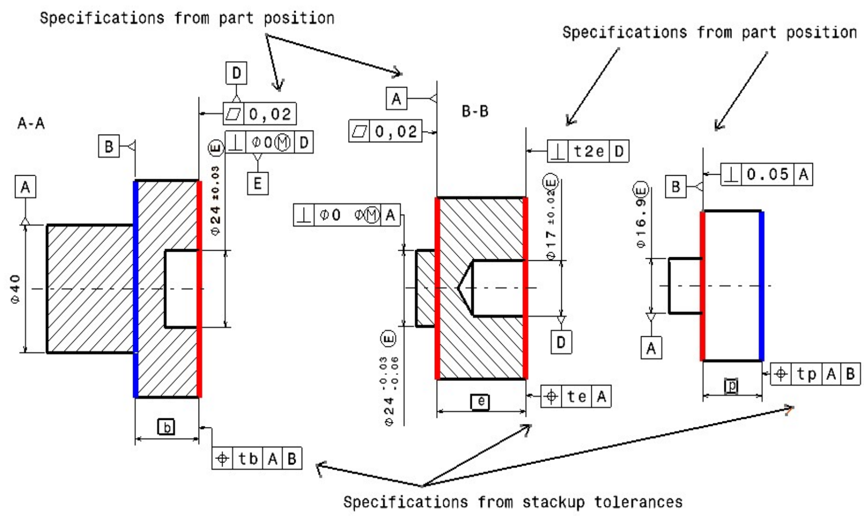

Fig. 9. Specifications of each part obtained from the part positioning and the tolerance stackup

To establish the tolerance stackups, we must consider a positive or negative sign for each dimension. The functional condition dimension will impose a positive direction starting from the joint surfaces of the assembly with the external environment and will be the reference system of the assembly. The final end surface will be the surface where the external environment is supported. In the case of one-dimensional stackups, this support will be a support with a TED orientation, that of the direction of analysis. Once the tolerance stackup has been drawn, each ISO dimension must be noted in the definition drawings of each part by means of position specifications in relation to the reference system of each part and by means of TED dimensions (see Fig. 10).

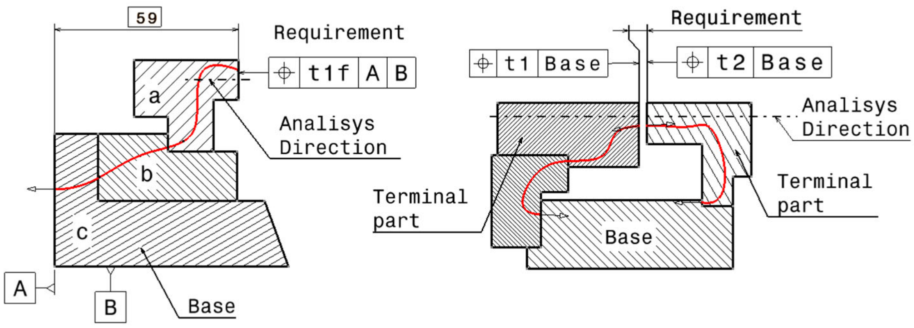

Fig. 10. Applicable types of tolerance stackups

This process is very suitable for position requirements with respect to a base part because one of the terminal surfaces belongs to the basis part. Supposing the terminal surfaces corresponding to a functional requirement belong to two or more parts cannot be considered as base parts. In the latter case, instead of a linear tolerance stackup, we have a loop of contacts with two linear branches that close at the base. In this case, orientation deviations or errors are very influential and complicate the ISO dimensioning considerably by requiring the introduction of orientation specifications and not only position specifications. The ISO dimensioning criterion, which is only possible using unidirectional tolerancing stackups [10, 14, 15], is that the line of analysis intersects the primary contact surface of the intervening parts. A generalisation for 2D or 3D tolerance stackups would be necessary, but this generalisation is beyond the scope of this paper.

2.7 Dimensioning for a functional requirement not linked to a contact. General tolerances

Functional analysis allows us to identify and narrow down functional requirements not linked to contacts between parts. This is the case of minimum safety clearance requirements between parts or assembly mountability requirements. The end surfaces of such geometrical technical requirements will require more stringent specifications than the general requirements (see Fig. 11).

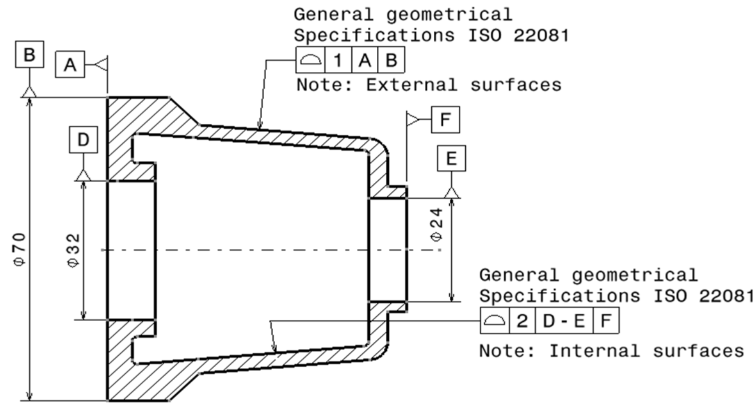

Fig. 11. General tolerances. Singular case of multiple datum systems

The general ISO specifications are determined by ISO 22081:2021 [16] but it does not distinguish between different possible functional zones of a part. When a mechanism has a group of different general surfaces it is possible and more convenient to distinguish several general reference systems for the same part [17]. For example, in a part with a housing or cover function, the outer general surfaces should be referred to a datum system that facilitates positioning it with respect to the external environment and the inner general surfaces should be referred to a datum system of positions of the inner block that they cover without contact. This extension is not included in the standard, so it would be necessary to write an explanatory note in each of the general reference systems established by ISO 22081:2021

2.8 Technical Dossier

All the documents, reports, tables, drawings and blueprints referred to in the previous sections are included in what is known as the technical dossier. This technical dossier includes the tolerance stackup dossier, part positioning dossier, the functional analysis dossier and all the plans and drawings used [18]. This dossier is very important for the company's capitalization decisions throughout the product's life cycle and makes it possible to check the validation of the project step by step and by all the parties involved (customer, suppliers, technical departments, etc.).

3 Case study. Application to an industrial assembly

To illustrate, we present an application based on the functional requirements of a centrifugal hydraulic pump. As a case study, we present the application to a functional requirement of a hydraulic centrifugal pump. In this case, the requirement, which we call Jg, represents the width of the peelable gauge (p). This value does not correspond to a predefined or measurable value, as it has to be determined when adjusting the pump assembly and the pump efficiency, since it implies an axial displacement of the pump shaft. Functional contacts between parts are intermediate elements such as bearings or flat seals, as is often the case in practice. This functional requirement, Jg, results in the operational condition, the positioning of the cover f and the one-dimensional stackup of functional dimensions shown in Fig. 12.

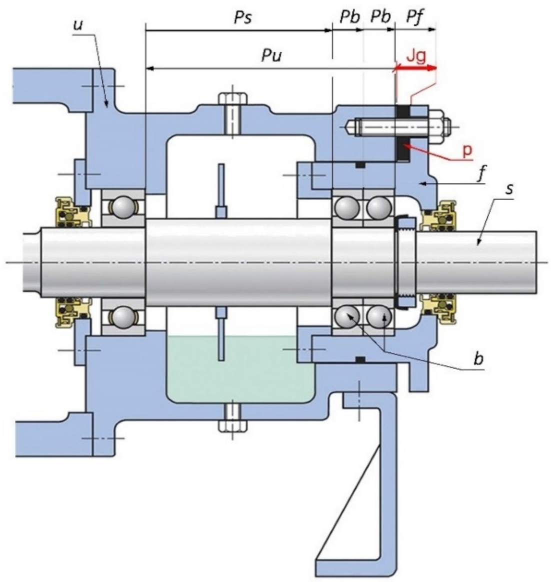

Fig. 12. Pump bearing unit

The first step in the process would be to identify each surface of each part. The identification of the flange surfaces (f) is shown in Figure 13.

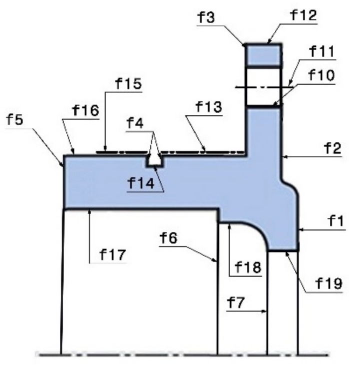

Fig. 13. Surfaces identification

With the entire identification of the surfaces of all parts involved in the requirement, we can accurately complete the flange positioning table (f).

COVER	f				
plane		cylinder		6 hole	
A	f2	B	f3	C	f4
contact 2 bearings contact		clearance		clearance 6 bolts M6 interference	
plane		cylinder		6 threaded holes	
D	b1 (bearing)	E	u1 (unit)	F	u2 (unit)

Table 1. Flange positioning table (f)

By means of the table we can transfer in an orderly and complete manner the ISO dimensions corresponding to the positioning of the flange (f), the body (u) and the bearings, which are the parts involved in the positioning of the seal (see Figures 14 and 15).

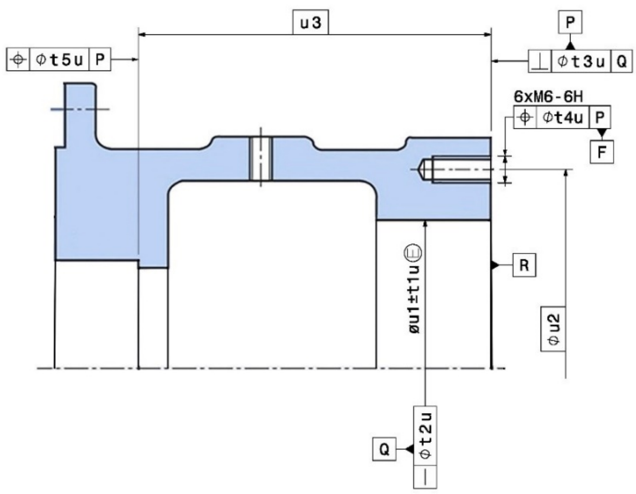

Fig. 14. Body (u) ISO dimensioning

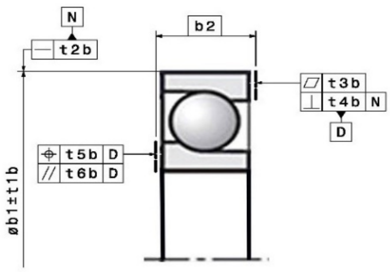

Fig. 15. Bearing (b) ISO dimensioning

The shaft is only involved in the dimensioning of the stackup Jp and not in the positioning of the flange (f). The ISO functional dimension corresponding to the stackup in Fig.13 is shown in Fig.16.

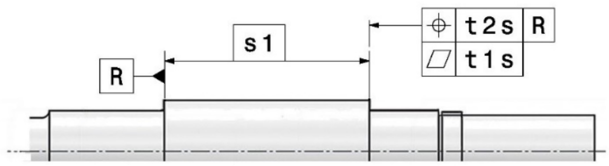

Fig. 16. Shaft (s) ISO dimensioning

Figure 17 shows the ISO dimensioning of the flange with the ISO specifications corresponding to its positioning, the operating state of the functional requirement Fg and its ISO functional dimension corresponding to the dimension string of the functional requirement.

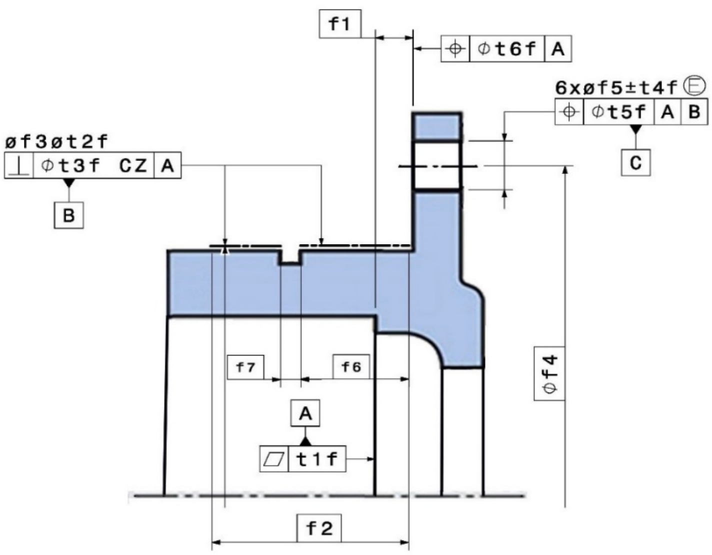

Fig. 17. Flange (f) ISO dimensioning

4 Conclusions

This article has presented a method for learning and approaching, from the functions to the dimensioning of each part of a mechanism, the determination of geometric specifications in the ISO-GPS language in the same way as it is done professionally.

The starting point is a technical solution with a nominal geometry, and it is the geometric functional analysis and detailed determination of the functional structure of a mechanism that makes it possible to determine the geometric functional conditions. However, in order to translate these assembly requirements into ISO specifications for each part, it is essential to analyze the positioning of the parts.

Part positioning and dimensional stactup are the elements that allow us to determine the ISO specifications. In mid-level professional practice, tools for functional and kinematic analysis, assembly processes and the use of spreadsheets are well known, but tools for analyzing part positioning and ISO dimensional chains are not so well known, which is detrimental to understanding the practical benefits of ISO functional dimensioning.

We have presented this method with a clear pedagogical approach: to facilitate the approach to ISO dimensioning with a procedure that allows to solve the simplest cases, but at the same time they are the most numerous. A simplified but practical method that allows you to understand the advantages and usefulness of ISO dimensioning by focusing on the whole and the function rather than on the part and the geometry.

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